A Method of Comparing the Costs of Platform and Unique Product Design

by

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Submitted to the Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

To help increase its competitiveness in the market for imaging products, Polaroid Corporation must speed up the process by which it designs and manufactures cameras, while simultaneously reducing costs. To this end, it is considering undertaking a platform design approach to its cameras, in which components and entire subassemblies are used across multiple, different camera products. The primary theorized benefits of such an approach are: reduced manufacturing costs, due to greater economies of scale and faster learning from using fewer unique parts for the same number of end products; and faster time to market for successive releases within a platform, due to design re-use. The latter can be equivalently expressed as fewer design resources needed to meet the same schedule.

A camera design team at Polaroid identified a portfolio of six new camera designs and which subassemblies could be shared. Through the creation and use of several sub-models, I quantified the total cost, from design through production, of two scenarios: the platform design approach, in which the subassemblies are shared across the six cameras as proposed by the design team, and the unique design approach, in which no components at all are shared. In order to keep the analysis focused on the cost difference between the two approaches, I assumed that in both scenarios the cameras would be priced the same and would sell in the same quantities.

The analysis shows that, for this particular portfolio, the platform design approach would cost 13.5% less than the unique design approach, a savings of $223 million over ten years.

In addition to the data generated for this specific portfolio, I created the following:

- An assemblage of historical design and manufacturing data which may be useful to Polaroid and similar companies
- A process by which the analysis can be repeated for other product portfolios
- A set of spreadsheet tools which can be reused for other product portfolios

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I. INTRODUCTION

Challenges

Polaroid's historical success is due in large part to its strategy of selling instant cameras at or below cost to create a large user base, and selling the corresponding film at a significant markup. For a constant "film burn" by users – that is, number of exposures per camera per year -- a larger installed base of cameras leads to greater sales of the highly profitable film.

However, the competitive environment has changed. In addition to the ever-decreasing price/performance ratio of 35mm cameras, two major threats to Polaroid's instant film business have emerged: Fuji Corporation's production of instant cameras and film, and digital photography. As a result, sales of Polaroid's instant cameras and film have leveled off and face a decline in Polaroid's mature markets. In the face of these challenges, Polaroid has decided, among other things, to focus attention on making cameras profitable by reducing development and production costs.

Additionally, Polaroid has decided to continue its penetration into the digital camera market. It already has two digital camera lines on the market – one OEM product and one higher-end unit, the PDC-3000, which retails for about $2000 and is aimed strictly at the professional user. Polaroid intends to continue to create products embodying its competencies in photography such as color filtering and exposure control, and integration with its PhotoMax digital image manipulation software. Despite these competencies, however, Polaroid realizes that there are many other variables that will determine success in the digital market, such as expertise in consumer electronics design, industrial design, time to market, and low-cost manufacturing; and even then, the profit picture in an already crowded market is not clear. Thus, in addition to the new focus on reducing camera costs, Polaroid has also decided to leverage its expertise – and larger profit margins -- in instant imaging by creating a series of hybrid cameras which produce both a digital image and an instant film image. Though the size of this market is unknown, the market is a niche that Polaroid should be able to dominate and one that leads to a stream of profitable film sales.

To meet these strategic objectives, a design team at Polaroid has proposed a portfolio of six cameras, three of which are digital, which span a range of price points, are targeted at different market segments, and cover two different instant film formats, but share a certain number of common subassemblies. This is the essence of platform design.

Platform vs. unique design approaches

The literature is rich with theories, models and case studies describing the pros and cons of platform design, as well as the organizational structures best suited to such an approach. Robertson and Ulrich (1998) define a platform as "the collection of assets that are shared by a set of products. These assets may include components, knowledge, and production processes." The benefits seen from product platforms are:

- Economies of scale in research and development, production, and service from sharing technology and components
- Faster time-to-market for variants of the initial platform
- Building product awareness and leveraging brand names by creating a consistent look and feel across a range of products.
- Mass customization: the ability to deliver multiple variants, at little incremental cost, in order to more precisely match individual customer requirements.
- Reduction in inventory achieved through postponement techniques; for example building the "vanilla" unit at a single factory, then installing the custom components at a distribution center closer to the customer.
- The ability to outsource the design and production of entire subsystems to suppliers, thus taking advantage of lower labor costs, higher expertise, and greater competitive focus.

Note that the latter three are not a direct result of the platform approach. In order to make these successful, the product design must incorporate some level of *modularity*. As with the term "platform," "modularity" has a range of definitions and variations [Ulrich, 1995] but at its most fundamental, it is the use of common interfaces between assemblies. If a unique or custom subassembly uses a common interface, it can easily be added to the "vanilla" unit.

The potential costs and pitfalls of a platform approach are:

- Greater time and resources spent initially to define and design the platform
- Compromises made in component selection: more expensive components are chosen for lower-end products, or features are left out of higher-end products in order to preserve commonality. The former increases costs, whereas the latter may reduce sales.

This research is based on a six-month internship at Polaroid Corporation. It focused on six major camera products, collectively referred to as the Next Generation Cameras. One of the cameras, referred to as the EIC, was the focus of nearly all of the design team's efforts, and reached the final prototyping stage towards the end of the six months. The other five cameras had been conceived and planned, but detail design had not commenced at the start of the internship. Since the research required defining the camera designs down to the component level, a large portion of the internship was devoted to working with the engineers to define the most likely component choices for each design.

In the remainder of the thesis, all data have been disguised, but are representative of the real data.

II. PRODUCT DESCRIPTIONS

Three of the six cameras are digital cameras. Digital cameras allow you to capture images onto a variety of electronic media, such as floppy disks or small memory cards. The images can then be loaded onto a personal computer and can be viewed, manipulated, and sent over the Internet. Physical copies of the images can be created with an inkjet or laser printer. Alternatively, hybrid cameras allow you to print a hard copy directly in the field, without having to download the image to a PC.

EIC: This camera is a hybrid digital and instant camera. Through one set of optics and a charge-coupled device (CCD) it takes and stores a digital image. Simultaneously, through another set of optics it exposes a traditional photographic image onto Spectra format instant film. The camera folds for compactness; in its folded state it will take a digital image but not a photographic image.

EIP: This camera, also hybrid, is essentially the EIC with the photographic exposure system removed and replaced with a miniature digital printer. From a user's perspective, the primary difference between the EIP and the EIC is that with the EIP the user can take dozens of exposures, then scroll back through the images (displayed on a small LCD screen) and choose which ones to print out. With the EIC, the decision to produce a print must be made before taking the picture.

ESC: A digital-only camera, this is essentially the EIC minus the photographic optics, exposure, and film transport system.

PIC: The EIC without the digital imaging system. As such, it is a replacement for Polaroid's current line of Spectra instant-film cameras. It is expected to appeal to customers because it is significantly more compact than the current line.

PMF: Similar to the PIC except that it uses 600-format film and has a less sophisticated ranging and focus system. It shares the same architecture, optics, shutter, and electronics, but because of its simpler design can be sold at a lower price point.

HB600: Similar to the PMF except that it is a "hardbody" as opposed to "folding" camera. While this sacrifices compactness, it significantly reduces the cost to design and manufacture, allowing it to be a replacement for the 636, Polaroid's "bread-and-butter" high volume, low cost camera.

Table 1 below summarizes the key features and attributes of the six cameras:

TABLE 1: Next Generation Cameras

	EIC	ESC	EIP	PIC	PMF	HB600
Digital Acquisition	Proprietary CCD	Proprietary CCD	Proprietary CCD	N/A	N/A	N/A
Digital Storage	SmartFlash	SmartFlash	SmartFlash	N/A	N/A	N/A
Image Manipulation	No	No	Yes	N/A	N/A	N/A
Film Imaging method	Direct exposure	N/A	Digital printer	Direct exposure	Direct exposure	Direct exposure
Film Format	Spectra	N/A	Spectra	Spectra	600	600
Photographic Imaging Shutter	stepper, 3 blades	N/A	N/A	stepper, 3 blades	stepper, 3 blades	stepper, 3 blades
Photographic Imaging Focus	10 zone quintic	N/A	N/A	10 zone quintic	2 zone solenoid	fixed focus
Ranging system	IR	Wink	Wink	IR	Wink	Wink
Flash Distance	10’	10’	10’	10’	10’	10’
Folding	Yes	No	No	Yes	Yes	No
Battery Type	AA, Film pack	AA	AA	Film pack	Film pack	Film pack
User Interface	Color LCD	Color LCD	Color LCD	1.5digit b/w	1.5digit b/w	1.5digit b/w

In order to quantify the benefits of platforms, we will compare two portfolios: the platform portfolio, in which some subassemblies are common; and the unique portfolio, in which no components at all are shared between cameras. We will refer to the platform portfolio as the NGP, for “Next Generation Platform,” and the unique portfolio as NGU, for “Next Generation Unique.” Table 2 shows the six products in the NGP, their subassemblies, and which subassemblies are shared across which cameras. The best way to read the table is to pick any one subassembly, then look down the column. Wherever a shade is common, that subassembly is common for the corresponding cameras. Where there is no shade (cell appears white), the camera does not contain that subassembly. Table 3 shows the six products again, this time in the NGU portfolio. As one can see, there are no subassemblies common to any two or more different cameras.

TABLE 2: Product-Subassembly Matrix, Next Generation Platform Portfolio

Camera	Viewfinder	Photometer	Flash Tube Ass'y	Misc. Electronic	EI Acquisition	CCD+Support PCBs	Inverter Board	IR Raning	Spread/Drive	PI Shutter	PI Focus	Door	Display LCD	User Interface	Mainframe Ass'y	Mainframe Flex	Power Board	Main Board	Front Plate/Final Ass'y	Packaging	Printer Module
EIC																					
EIP																					
ESC																					
PIC																					
PMF																					
HB 600																					

TABLE 3: Product-Subassembly Matrix, Next Generation Unique Portfolio

Camera	Viewfinder	Photometer	Flash Tube Ass'y	Misc. Electronic	EI Acquisition	CCD+Support PCBs	Inverter Board	IR Raning	Spread/Drive	PI Shutter	PI Focus	Door	Display LCD	User Interface	Mainframe Ass'y	Mainframe Flex	Power Board	Main Board	Front Plate/Final Ass'y	Packaging	Printer Module
EIC																					
EIP																					
ESC																					
PIC																					
PMF																					
HB 600																					

These matrices help describe the basic architecture of the cameras in the portfolio. To create a cost model, we need to go a step further: we need to know exactly which components (not just subassemblies) are shared in each camera, their quantity, and cost to Polaroid. In other words, we need Bills of Materials for all six products in each portfolio.

III. SCOPE AND KEY ASSUMPTIONS

By definition, a model is a simplification of the real world. A street map, for example, might show you where certain buildings are located, but it won't tell you the layout of rooms inside the building. A model that is as rich and complex as the real world is of no use, since the real thing already exists. The simplification inherent in a model allows you to draw conclusions and make decisions more quickly and cheaply than through trial and error. The key assumptions, inclusions and exclusions in this model are described below.

Key Assumptions

Revenue Neutrality. This analysis looks only at the costs of each portfolio, not the revenue. In other words, I assume that in both portfolios, the same volume of each camera is sold at the same price. Accordingly, revenue and profit are absent from the analysis.

Modularity. Within Polaroid, the platform concept is often referred to as "modularity." In fact, as described previously, these are two separate but related concepts. With regards to modularity, in planning the NGC portfolio, some attention was paid to using common, easy-to-manufacture interfaces, so that multiple variants of a single product (e.g., the EIP) could be offered. These variants might arise over time; for example, as technology becomes more affordable, successive releases might have a higher-resolution CCD or LCD. These variants might be available simultaneously: certain features available or not, different colors and styling, or differences specific to regions, such as the format of a video out signal.

However, this analysis does not address modularity and the associated mass customization capabilities and costs. It focuses on a different platform question – what is the benefit from sharing designs and components across significantly different products? As such, with one exception the analysis assumes only one version of each of the six major products in the NGC portfolio. The exception is in the analysis of manufacturing costs, where a more realistic total number of variants is needed and can be approximated without knowing exactly what those variants might be.

Unique design. One of the possible costs of the platform approach is sub-optimizing the design of one or more products in the platform in order to gain the benefits of commonality. The choices of what to share seemed reasonable and did not have clear, cheaper alternatives. Where it is clear that commonality doesn't make sense, uniqueness was preserved. For example, the Product-Subassembly matrix shows that only a few components are in common between the low-end HB600 and the high-end EIP.

Thus, for each camera in the NGU, I assumed the exact same part counts and costs as its counterpart in the NGP, the difference being that with the unique designs, none of the parts are shared with any other camera. In other words, I assumed no compromises were made in the NGP.

With any platform, the product where the greatest cost compromises (more expensive components than necessary) would occur would be in the "low-end" – the product with the fewest features and the least expensive components. In the Next Generation platform, this is the HB600. Without having to redesign the HB600 uniquely, we can apply two tests of the assumption that no compromises were made.

The first test is to compare the material cost of the HB600 with that of the 600-format camera currently in production: the 636. This camera was originally designed uniquely, and has been improved over time with no platform compromises. If the HB600 material cost is the same as that of the 636, it would indicate that no significant compromises impacting material costs were made. To perform this comparison, we must project the materials cost of the HB600 at a point in the future when its design will be the same age as the 636 now, since materials costs have historically declined due to renegotiations with suppliers and continuous design improvement. Historically, Polaroid's products have reached "maturity" – the point where cost reductions become minimal – when unit costs are approximately 50% of the cost at design release. The 636 is a "mature" product, and thus has approximately reached its minimum cost. By comparison, the cost of materials in the HB600 must decline by 54% to equal the current 636 cost. Because this is near the approximate 50% historical reduction, it appears that the HB600 design has not been significantly compromised in order to fit in the platform. This test is imperfect because it uses historical data which may be inaccurate and variable, and which may not be applicable to future conditions.

The second way to test the no-compromise assumption without undertaking a redesign is to examine the current design for any unused components or interfaces, and to quantify their incremental cost – that is, the additional cost of the components minus the savings achieved from higher volume purchasing discounts. In the HB600, the only unused "components" are portions of the microcontroller code used for features found in the other cameras in the portfolio. Aside from the minimal cost of "commenting out" that code, there are no initial or recurring costs for this unused code. This test is imperfect because it does not question whether a particular component is the cheapest that can be found to do the job – only whether it is used or not.

Several Polaroid personnel pointed out that if a team was chartered with designing an ultra low-cost 600-format hard body camera, with no requirement that it be part of any portfolio or share any components with the 636, the team would probably find ways to make the camera cheaper than both the HB600 and the 636. In this sense, they argue, the HB600 is in fact compromised. If and when the low-cost 600 camera is designed, it will be useful to revisit this analysis to comprehend the true costs of compromise.

Manufacturing. The Next Generation Cameras are assumed to be manufactured largely the same way Polaroid cameras are currently:

- Injection molding tools are designed and purchased by Polaroid, but installed at suppliers who make and deliver the parts
- Assembly is done at Polaroid's Vale of Leven (VOL), Scotland site
- Subassemblies are built with automated assembly equipment (Sony robots) if volumes are greater than 1,000,000 units per year
- Final assembly is performed manually in U-shaped cells
- Printed circuit board assembly is outsourced

Financial

- Cost of capital = 20%
- Inventory carrying cost = 30% per year
- Ten-year horizon
- A fixed annual sales volume for each of the six cameras is used. Some of these products have lives of less than ten years, but are assumed to be replaced sequentially with versions with incrementally upgraded features, such as higher resolution LCD displays or software features.

Included Costs

Product development cost. This is the cost of product design, from conception until the start of production. About 80% of this cost is engineering labor hours, with the rest going to such things as lab equipment, CAD equipment, prototyping, and general overhead.

One of the benefits of platforms is the faster time-to-market of successive releases from the platform. This can be, and for this analysis is, expressed as fewer product development dollars, since we are looking at only costs, not revenues. A simple way to think about this normalization is: with the platform approach, there is one team releasing products sequentially; with the unique approach, there are six different teams each working on one product and releasing them at the same time as the platform team would release its products.

Manufacturing development cost. This is the cost of preparing the product for production, and consists primarily of engineering labor. The single largest category of manufacturing development cost is injection molding tooling design for plastic parts. There are also significant resources from the manufacturing plant focusing on designing the products for manufacturability, as well as designing and sourcing the assembly fixtures and stations.

Inception cost. This is the cost of "ramping up" production until a steady-state unit cost is achieved. It includes the extra labor and yield loss required to travel down the learning curve, as well as premium and expedited charges for such things as material third-party engineering.

Capital. This is the equipment required for production: mold tooling, assembly fixtures, and testers.

Material. The cost of the camera components.

Overhead. The cost to run the factory and support production, including such costs as material handling, engineering, and supplier management.

Labor. The direct labor required to assemble the cameras.

Inventory Carrying Cost. The cost of capital tied up in inventory, and the associated storage, handling, and shrinkage costs. As described later, this analysis includes only raw material inventory and factory work-in-process.

Excluded Costs

Research. One of the potential benefits of platforms is the amortization of research over multiple products. In this case, the only notable research would be for the CCD, which has already been amortized over previous products. As such, no research dollars are included.

Floorspace. As the analysis will show, the difference in factory capital between the NGU and NGP is just 2% of the total savings. Required floor space, which correlates with factory capital, is thus insignificant and does not warrant the measurements and data-gathering required.

Finished Goods Inventory and Distribution. Once the cameras are fully assembled, there is no difference between a unique camera and one that is part of a platform. Accordingly, inventory from finished goods through to the customer is not part of this analysis.

One of the possible benefits of modularity is the tactic of assembly postponement. A cursory analysis of the product design was performed to assess the level of modularity in this platform and the potential significance of postponement tactics. The analysis shows only one clear candidate for postponement: the SmartFlash card which stores digital images. Instead of installing this at the factory, Polaroid could install this at the distribution center, or even give customers a coupon to buy one for themselves. This opportunity is identical for both the unique and the platform portfolios, so it is excluded from the analysis.

Service. With fewer part numbers, the NGP should cost less to service than the NGU, because of 1) fewer repair parts to stock 2) possibly fewer failures, and 3) faster learning curve for the service personnel. Because the return rate for Polaroid's current products is less than 2%, and only a fraction of those returned are repaired, the differences are not likely to be significant. Thus it was deemed not worthwhile to gather the relevant data and model the difference.

IV. ANALYSIS PROCESS

The total cost model is comprised of several sub-models, which depend upon each other to varying degrees. Some of the sub-models are simple equations, which can be calculated manually, with parameters derived from real and projected data. Others depend upon Excel spreadsheets for their structure and calculation. These spreadsheets are reusable, so that other scenarios with different assumptions and inputs can be evaluated. The flexibility of these models are dependent on the types of inputs being changed.

Appendix A shows the sub-models of the total cost model, which ones are represented by reusable Excel spreadsheets, and how they are all connected. The following sections describe each sub-model's assumptions and structure. Together, these constitute an analysis process by which other platform scenarios can be evaluated.

For the simpler models, all calculations specific to this project are included in these sections. These simpler models are:

- Inception
- Labor
- Inventory

For the more complex spreadsheet-driven models, some of the calculations are detailed in the appendices. These more complex models are:

- Material
- Development
- Capital
- Manufacturing Overhead

Material

The heart of the entire analysis is the Material Model, a spreadsheet which takes as input part types, quantity per product, and costs at a starting volume, and outputs a total materials cost. It also outputs a total unique part count, an important parameter used by some of the other models.

The fundamental premise is that there are economies of scale achieved by sharing parts across multiple products, since you decrease the unique part count and increase the volume per part. Scale economies differ from part to part, however. Since it's not realistic to know the cost curve for every single part, I found it useful to classify the parts into major types. Then, within the Material Model, average scale economy rules are applied to these types.

These values were used for the analysis and represent engineer's estimates and analysis of piece part quotes:

- Mechanical and Optical: 5% reduction in price for every doubling of volume
- Molded: 40% reduction in price when doubling the number of cavities per tool
- Electronic, including PCB assembly charges: 25% reduction for every 10X increase in volume

These values may serve as a reasonable starting point for other types of products as well.

The required part information comes from the Bills of Materials for each product, for the NGP and NGU. The following process creates the material model in a standard Excel spreadsheet

1. Ensure that each part on each BOM has an identifying number, quantity per unit of end product, cost at a standard volume, part type (mechanical, electrical, etc.) and the forecasted demand for that product.
2. Concatenate all of the BOMs in a given portfolio.
3. Sort by part number to see where parts are shared
4. Using pivot tables, or manually editing the spreadsheet, consolidate repeated part numbers and the associated total demand.
5. Apply the scale economy rules to each part, based on its type and its projected annual volume, to calculate its new cost.
6. Calculate the total cost of producing all the products in the portfolio at the forecasted demand levels.
7. Do this for all portfolios and compare results.

Figure 1 illustrates this process:

FIGURE 1: Creating The Material Model For A Given Portfolio

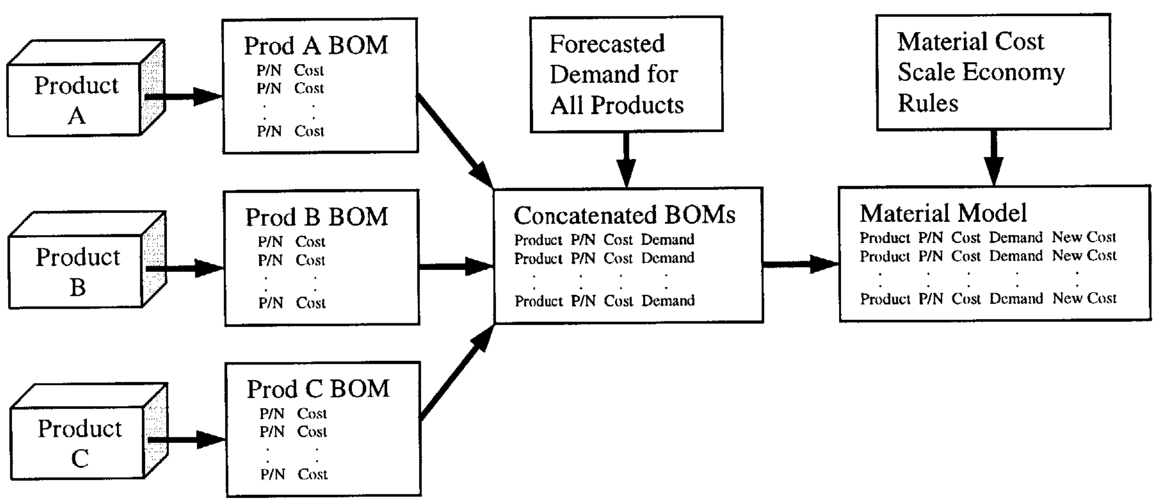


Table 4 shows an example of concatenated BOMs. Table 5 shows the Material Model, which are the concatenated BOMs after sorting and introduction of the scale economy rules. For simplification, the example assumes a quantity of 1 for each part in a given product and assumes that all parts are of the same type and therefore subject to the same scale economy rule. Note that part number 3 is used in both products A and B; parts 5 and 7 are shared across products B and C.

TABLE 4: Concatenated BOMs Example

Product	Part Number	Cost at 100K units/yr	End Product Demand, units/yr
A	1	$0.17	100000
A	2	$0.43	100000
A	3	$0.23	100000
A	4	$0.82	100000
B	3	$0.23	300000
B	5	$1.14	300000
B	6	$0.76	300000
B	7	$0.06	300000
C	5	$1.14	500000
C	7	$0.06	500000
C	8	$0.39	500000
C	9	$0.65	500000

TABLE 5: Material Model Example

For every doubling in volume, part prices reduce by:				**10%**
Product	Part Number	Cost at 100K units/yr	End Product Demand, units/yr	Cost at Forecasted Demand
A	1	$0.17	100000	$0.17
A	2	$0.43	100000	$0.43
A, B	3	$0.23	400000	$0.19
A	4	$0.82	100000	$0.82
B,C	5	$1.14	800000	$0.83
B	6	$0.76	300000	$0.64
B,C	7	$0.06	800000	$0.04
C	8	$0.39	500000	$0.31
C	9	$0.65	500000	$0.51
			Total Material Cost	$1,516,448

Appendix B gives more information on the specifics of the model and calculation for this project.

Development

Product development cost is called "Big D" at Polaroid and is denoted by D. Likewise, "little d" refers to manufacturing development cost and is denoted by d. Product development refers to the process of conceptualizing, designing, and readying a product to be handed off to manufacturing. For the Next Generation Camera platform, it includes:

- Planning the Next Generation portfolio
- Defining feature and performance specifications
- Designing and drafting the mechanical components and interfaces

- Designing and drafting electrical schematics
- Writing software code
- Selecting and procuring components
- Hiring industrial designers to create a unique look and feel to the product
- Creating and testing prototypes

Manufacturing development consists of two primary activities: ensuring the product design is manufacturable, and designing and sourcing manufacturing equipment. D and d are tracked separately because product development and manufacturing development personnel typically come from different functional groups, though they are on the same product team. For the purposes of my analysis I pooled D and d, for these reasons:

- The distinction between product and manufacturing development is fuzzy. There is a lot of overlap in the design process of the product and manufacturing development functions, with multiple people performing both roles. Discerning exactly what people did when is difficult.
- It does not matter who performed product development and who did manufacturing development, because the primary variables which drive big D, such as part count, are the same which drive little d.

The goal was to create a predictive model for D+d which would allow me to estimate development costs for the NGP and NGU in advance. I had at my disposal two main sets of data to help me develop the form and parameters of an equation for D+d. They were:

1. Development data from the EIC program, which by the end of the internship was 90% complete.
2. Data from past camera development programs.

The EIC data had several advantages: it was the most current, the most detailed, and the most relevant to the Next Generation platform, since the EIC is a digital camera and since it was developed by the same team that would be developing the rest of the platform. Using data from past programs would implicitly introduce more variables into the equation: different types of cameras, different teams with different levels of experience, different management styles and effectiveness. It would also introduce greater error into the analysis, since the past program data were less complete and detailed. However, the potential added richness of the data made it worth investigating. Regression analysis, whereby I attempted to find a correlation between development cost and number of parts by type and complexity, showed no clear relationship, so I chose to rely exclusively on EIC data.

I applied an Activity-Based Costing approach [Kaplan and Cooper, 1998] to the EIC data to establish a linear equation describing D+d. D+d has two primary components:

1. Labor: the fully loaded cost to Polaroid of the employee hours devoted to the EIC project. This constituted over 80% of the total cost.
2. Expenses: all non-labor costs, including everything from office supplies and travel to consultants, lab equipment, and prototype manufacturing.

I followed this process to arrive at the equation for D+d:

1. Define the major activities within D+d and quantify the amount of labor spent on each using time report record. For example, there were 42,226 person-hours of mechanical design.
2. Allocate expenses uniformly to all labor hours. This was valid because the expenses didn't appear to be concentrated on any particular activity and because expenses were a relatively small (<20%) portion of total D+d.
3. With the standard fully-loaded labor rate, plus the expense allocation, calculate the total dollars spent on each activity.
4. Define a single driving variable for each of the activities. For example, the primary driver of "mechanical design" is "number of unique mechanical parts." While many things drive the amount of mechanical design hours, part numbers is the most direct and reasonable proxy. This determination was made through interviews and surveys.
5. Divide the driver quantity into its associated activity to arrive at the amount of activity per unit of driver. For example, we divide 158 mechanical part numbers into the $6,776,000 spent on mechanical

design and find $42,886 per mechanical part number. The sum of these relationships constitutes a multi-variable linear equation for D+d.

The activities and drivers for D+d were defined as follows:

TABLE 6: Development Activities and Drivers

ACTIVITY	DRIVER
Mechanical Design	Number of unique mechanical parts
Electrical Design	Number of unique electronic parts
Purchasing	Total number of unique parts
Final Assembly Cell Design	Number of major products
Product Documentation	Number of major products
Program Management	Fixed (no driver)
CAD Object Library Design	Fixed (no driver)
Platform Planning	Fixed and specific to NGP only

The resulting equation is:

$$D + d = \$42{,}886M + \$43{,}153E + \$523T + \$419{,}148P + \$1{,}000{,}000NGC + \$978{,}707$$

where:

$D+d$ = Total product and manufacturing development cost
M = Number of unique mechanical parts
E = Number of unique electronic parts
T = Total number of unique parts = M + E
P = Number of major products
NGC = 1 for the Next Generation Platform portfolio, 0 for the Next Generation Unique portfolio

With those variables known for the NGP and NGU, D+d can be calculated. Appendix C contains a full derivation of the equation from EIC data, and the calculations for the Next Generation Camera portfolios.

Capital: Mold Tooling

Mold tools are equipment used to make plastic injection molded components, ranging from small gears to complex external shells. The "tool" itself is the set of steel plates into which molten plastic is injected, and are custom-formed to the specific part design. The custom form is referred to as the mold cavity. The tools are then installed into standard injection molding machines. Except for optical components, Polaroid outsources both the manufacturing of the tools and the production of parts with those tools. Polaroid pays a one-time amount for the creation of each tool, and then pays for each plastic part produced with the tool.

The *price of each tool* is dependent on several factors: the number of cavities per tool, the complexity of the particular part design, the tolerances required, and market conditions. To simplify the analysis, I calculated the average price of a single-cavity mold tool for the EIC camera.

The *number of tools required* for each part type is simply the forecasted demand divided by the effective capacity per tool. The effective capacity is again dependent on the particular part design. A very simple part with thin walls requires little plastic and a short cooling time, so the associated tool will have a very high production capacity. A large, complex part, with multiple actions (moving components inside the tools) and thick walls, will require more injection time and cooling time; thus the associated tool will have lower capacity. To simplify the analysis, I classified all parts as simple, average, or complex, and associated an average capacity for each part type.

When demand for a particular part exceeds the capacity of one single-cavity tool, it is more cost effective to create a multiple-cavity tool than to purchase multiple single-cavity tools. The average increase in price is 40% for every cavity doubling (100% capacity increase).

Beyond immediate capacity requirements, additional copies of each tool are required so that when repair to a tool is needed, its backup can quickly be swapped in to minimize impacts to production. Interviews I conducted revealed that on average there are twice as many tools in existence as needed for immediate production.

With these guidelines, the mold tooling cost equation takes the following form:

$$M = \sum_i \frac{2D_i}{C_i \cdot n_i} \cdot P_i (1+a)^m$$

where:

M = Total mold tooling cost
D_i = Forecasted demand for part i
C_i = Capacity per cavity for part i
= 500,000 units/year for simple parts
= 300,000 units/year for average parts
= 100,000 units/year for complex parts
n_i = Number of cavities per tool for part i
= 1 if $D_i < C_i$
= 2 if $C_i < D_i < 2C_i$
= 4 if $2C_i < D_i < 4C_i$
= 8 if $4C_i < D_i$
P_i = Price of single-cavity tool for part i
a = Percent increase in tool price for every doubling in cavities per tool (= 40% in this model)
m = Number of doublings of cavities per tool

The unit *price of each part* as paid by Polaroid to its supplier typically decreases as the number of cavities per tool increases, since the supplier can amortize overhead and mold equipment depreciation over more parts. The average decrease in price for every cavity doubling is 40%. The price per part is then:

$$P = P_0 (1-a)^m$$

where:

P = Price of a part
P_0 = Price of a part at a starting volume (here, the EIC's 100,000 units per year)
a = Magnitude of the percent decrease in part price from cavity doubling
m = Number of doublings of cavities per tool

These formulas and logic are embedded in the Material Model. Please see Appendix D for the calculations specific to this model.

Capital: Factory Equipment

As contrasted with Mold Tooling, which resides with suppliers, Factory Equipment refers to everything else, which resides in Polaroid manufacturing facilities:

- Automated equipment for subassemblies
- Manual assembly equipment, such as small presses and welders
- Fixtures, tools, benches, and racks
- Testers

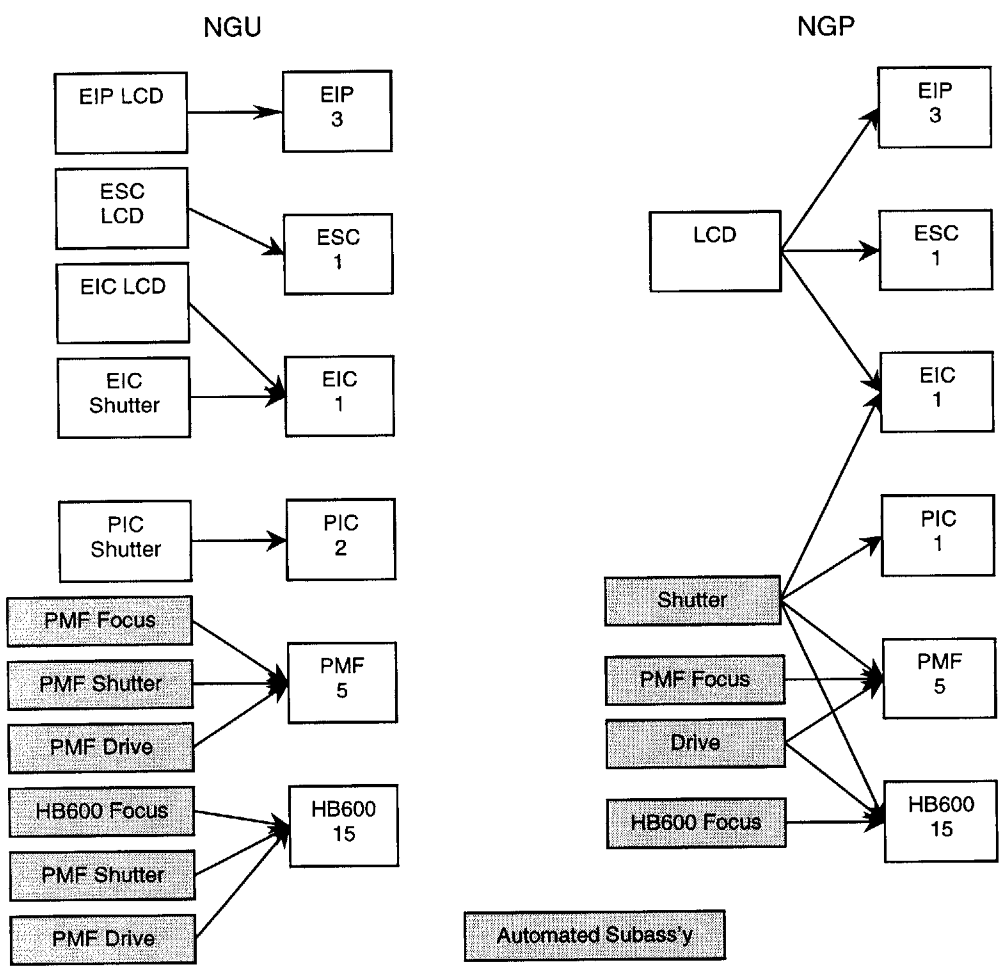
There are three general categories of assembly processes at the Polaroid factory:

- *Manual subassembly*, in which camera subsystems are assembled by hand, with or without the assistance of manual assembly equipment
- *Automated subassembly*, in which camera subsystems are assembled automatically by a series of pick-and-place type robots.
- *Final assembly*, where subsystems and other components are assembled manually and tested automatically.

Capital cost savings from the platform approach arise in two circumstances:
1) The commonality of components allows you to share equipment which would have otherwise been utilized at less than maximum capacity;
2) The commonality of components brings the total volume up to a point where it is economically beneficial to automate the assembly.

To see where the sharing and automation opportunities are for the two portfolios, I constructed a process flow diagram (Figure 2) for both the platform and unique approaches. Interviews with manufacturing and product engineers gave me the key guidelines needed to create this diagram. Those guidelines are detailed in Appendix E.

FIGURE 2: Process Flow Diagram



The numbers in the final assembly cells refer to the number of cells needed to meet demand. The differences in moving from the NGU to the NGP are as follows:

- The LCD subassembly for the 3 digital cameras (EIC, ESC, EIP) can be centralized.
- The PI shutter subassembly for the EIC and PIC can be automated, since it is now identical to the PMF and HB600 shutter.
- The spread/door/drive subassemblies for the PMF and HB600, previously on separate automation lines, can now be consolidated onto one automation line.
- One of the PIC final assembly cells can be eliminated, and the EIC cell can absorb its production. Since the EIC and PIC cells are then at full capacity, it is not necessary to share them with the PMF.

Appendix E details the cost analysis associated with these differences as well as the total amount of factory equipment needed for each portfolio.

Inception

For each major new camera product, Polaroid plans for initial costs it calls Inception. These are operational costs associated with ramping production up to a "steady state" and include such things as:

- Assembly time learning curve
- Indirect labor support costs
- Overtime costs
- Final assembly yield learning curve
- Material yield curve
- Air freight costs
- Higher materials prices from suppliers until volume is reached

It is usually planned that when some cumulative volume or time is reached, these costs will drop to zero. This planned volume or time varies from product to product, but is generally 6 months or 100,000 units, whichever comes first. In the case of the EIC, inception costs are forecasted to be \$1.086M over a period of six months. This comes from a bottoms-up detailed estimate.

What are the variables which drive inception costs? Interviews and data from past programs indicate two primary variables: number of parts and their complexity, and capacity. Capacity – as distinguished from volume – is the amount of equipment and labor needed for the planned production volumes. Inception scales fairly linearly with capacity. For example, if you double your capacity from 100 to 200 operators, then twice as many operators need to travel the learning curve.

Number of unique parts by itself may not be an accurate enough measure, since different types of parts incur different levels of inception costs. For example, a resistor on a circuit board will require virtually no inception, whereas a complex moving part will require more learning in assembly and quality.

Because I have the detailed inception estimate for the initial product, the EIC, I can model inception for the NGC portfolios empirically and solve for a generalized "cost coefficient" with the formula below.

$$\text{Inception} = \alpha \beta \sum a_i x_i$$

where:

α = capacity scaling factor, set to 1 for EIC
β = cost coefficient
i = part type as shown in table below
x_i = quantity of part type i
a_i = complexity coefficient of part type i

The table below shows the complexity coefficients for each part type and the quantity for the EIC and the NGC portfolios. The complexity coefficients come from interviews with product designers.

TABLE 7: Part Type and Inception Complexity Coefficients

Part Type	Examples	Complexity (a_i)	Part Count (x_i)		
			EIC	NGP	NGU
Discrete electr.	Resistors, caps	0	*irrelevant because $a_i = 0$*		
Static mech.	Brackets, screws	1	98	243	418
Optical	Lenses	2	12	15	42
PCBs		3	7	25	38
Dynamic	Gears, rollers	3	59	108	241

Given inception, α, a_i and x_i for all i for EIC, we solve for β and get \$3331 per "complexity unit."

For the NGC portfolios, we need to change the capacity scaling factor α. Interviews indicate labor capacity, as opposed to equipment capacity, is the primary factor driving inception. From paid labor hours per camera, we calculate that we need 344 direct labor heads for the NGC portfolio, and 38 for the EIC. Therefore, since we set α to 1 for the EIC, for the NGC portfolio it is 344/38. Using β = \$3331 and the part count data, we calculate inception costs of:

\$20,263,700 for the NGP
\$41,281,258 for the NGU

Labor

In this model, after inception the labor hours per camera is assumed to reach a constant. For the steady state, constant labor hours per camera we use the following estimates, derived from existing cameras and VOL estimates, for the unique portfolio:

TABLE 8: Labor Hours For Next Generation Unique Portfolio Cameras

CAMERA	PAID HOURS PER 1000 CAMERAS
EIP	400
EIC	700
ESC	100
PIC	500
PMF	350
HB600	180

Multiplying this by the annual volume per camera, and assuming 230 production days per person per year and 8 hour per production day, we get 344 direct labor employees.

We have not modeled any possible post-inception difference in the number of labor hours per camera between the platform and unique portfolio. In reality, the labor hours per camera may continue to decline slightly as the average experience level of the operators continues to increase, and there may be a difference in the rate between the platform and unique portfolios. This was not believed to be significant.

As described in the Capital chapter, the sharing of subassemblies in the platform portfolio allows the use of automation. Specifically, the EIC and PIC shutter can be assembled automatically, resulting in elimination of labor as calculated below:

The industrial engineer's estimate of the assembly time for this subassembly is 36.5 seconds. The total labor cost is then:

400K units per year x 36.5 person-seconds per unit / 3600 seconds per hour / 2000 hours per year / 62.5% rate efficiency = 3 persons.

Therefore the platform portfolio requires 341 direct labor employees, versus 344 for the unique portfolio. Assuming salary plus benefits cost of $40,000 per person per year in Scotland and annual wage increases of 5%, the labor costs over 10 years are:

NGU: $61,403K
NGP: $60,867K

Manufacturing Overhead

One of the theorized benefits of the platform design approach is that total manufacturing overhead is reduced, since by sharing components and subassemblies you reduce:

- Material handling
- Vendor management
- Equipment maintenance and upgrades
- Quality problems

What do we mean by "manufacturing overhead?" At Polaroid, for the Vale of Leven (VOL) profit center, it is all costs not including material and direct labor, and it is divided into three components:
Indirect Headcount. All labor except for direct labor, this includes managers, material handlers, product engineers, equipment engineers, industrial engineers, quality control engineers, technicians, supplier managers, purchasers, planners, finance personnel, and site maintenance personnel.
Expenses. This is every non-labor cost at the VOL, except for product material. It includes everything from electricity to travel and entertainment.
Equipment Depreciation. Since the initial expenditures are captured in the Capital part of this analysis, depreciation is not modeled here. One could modify the model such that capital expenditures are depreciated as expenses over time.

Overhead Today

In order to model the impact of platform design on overhead, we need to better understand the relationship between overhead and product characteristics. Currently, Polaroid's method of allocating costs to products does not adequately describe that relationship, for two reasons:

1. The method assumes all factory overhead (including depreciation) is variable with production volume, and allocates that overhead over the number of units produced.
   This is a distortion because not all overhead is truly variable with volume. A demand reduction, for example, does not immediately result in the elimination of equipment and labor.
2. Amongst different product types, overhead is allocated in proportion to the number of direct labor hours it takes to assemble each camera type.
   This is a distortion because many variables drive overhead, and direct labor may not be an adequate proxy for those variables. For example, a product may be very quick to assemble, using up a proportionally small amount of direct labor, but require significant testing or have significant quality problems, thereby using up a proportionally larger amount of equipment or engineering labor.

Furthermore, as described in the Labor section, we assume no difference in the assembly time between products in the platform portfolio and their equivalents in the unique portfolio. Yet we know intuitively that fewer part numbers should result in less overhead, as described at the beginning of this chapter. Therefore, we regard labor hours per unit as an inadequate descriptor of the differences in overhead.

Approach

To better understand the relationship between production volume, product characteristics, and overhead, I spent two weeks in the VOL factory, interviewing over 30 managers, engineers, planners, operators, and financial analysts, and touring the warehouse and manufacturing floor. The objective was to gather enough data on current operations there to perform a one-time Activity Based Costing analysis. From this analysis, a model was constructed to predict overhead for the NGC portfolios. Also gathered was data critical to the analysis of capital costs.

The costs were divided into five basic categories, defined here and explained further below.
Volume-Driven Headcount. Labor for activities which are primarily a function of production volume.
Project/Priority-Based Headcount. Labor used either for one-time, finite-length projects, or for "optional" continuous improvement projects.
Fixed Headcount. Managers and facility maintenance workers.
Activity-Based Headcount. Indirect labor supporting production.
Expenses. Non-labor costs.

Volume-Driven Headcount

This headcount was quantified through a survey of every department manager in the VOL factory. The survey asked each manager to define, of his or her direct reports, how many were "variable" with respect to production volume, and how many were "fixed." Of course, if production volume is zero, then there would be no need for any headcount, so at low to zero production all heads are "variable." To reflect the fact that at some minimum volume a step function increase of support is required, the question was phrased, "If production volumes were cut in half, how many headcount could you reduce?"

The model assumes that these categories are independent and can thus be linearly combined. Reality is more complicated than that: "volume-driven" employees are not actually different people than "activity-based" employees. They are one and the same. However, the model is accurate to the extent that reduced production volume reduces the amount of activities to be performed, and to the extent that that can be estimated.

With volume-driven headcount and actual production volume known, we have a simple ratio that defines the amount of volume-driven indirect labor per camera. Applying this to forecasted demand for the NGC portfolios would assume that the cameras in the NGC portfolio are identical to the cameras currently in production. While this is clearly not the case, a reasonable approximation can be made by equating cameras of similar complexity. In this case, the HB600 and ESC are approximately equivalent to the 600-line of cameras currently in production; the EIC, EIP, PIC, and PMF are approximately equivalent to the 7000 line of cameras currently in production. Further accuracy could be obtained by modifying the predicted headcount by a ratio of complexity of the new cameras to the complexity of the current cameras. Total part count would be an appropriate measure of this complexity.

Project/Priority-Based Headcount

At the time of the analysis, 11 employees were working on one-time, finite-length projects; for example, the implementation of SAP software. As these projects were not anticipated for the future, I set them to zero for the NGC portfolios. One could argue that there will probably always be some level of one-time, finite projects, so it would be reasonable to keep some positive number for the NGC portfolios. The number would be the same for the platform and the unique portfolios, however, because none of the current projects would be affected by the platform vs. unique question.

The 15 "priority-based" full-time-equivalent heads consisted of continuous improvement projects that could not be directly tied to ECNs or the regular kaizen activities performed in the factory. Those projects may be necessary to meet cost reduction or quality improvement goals; or they may be unnecessary. In any case, I could not definitively tie them to any specific driver and so chose to more roughly model this "chunk." For the NGU portfolio, I assumed that the 15 would remain the same. For the NGP portfolio, I reasoned that these continuous improvement activities, while difficult to model, are probably a complicated function of number of ECNs, number of part numbers, number of pieces of equipment, and other variables. Since these drivers tend to be a 1/3 to 2/3 less for the NGP, I assumed 50% less, and halved the 15 to 7.

Fixed Headcount

The model makes the implicit assumption that the organizational structures for the NGP, NGU, and current production are identical. This is shown by the fixed headcount, which includes "Administration" and remains the same for all scenarios. In reality, with different products and different production volumes, Polaroid management might decide to reorganize the factory. For example, it could move towards product teams, where instead of having, say, a central pool of technicians, specific technicians would be assigned to and responsible for specific products. During my interviews, several such scenarios were laid out. However, none of them had significant differences in total managerial headcount, so I left that in the Fixed category.

The other component of fixed headcount is the collection of facility maintenance workers. For some level of production greater than zero, these people are necessary to keep the building facilities running.

Activity-Based Headcount

This category covers activities which are clearly driven by certain variables. The process for modeling the activity-based portion of overhead is as follows, with examples:

1. Break down headcount into relatively homogeneous activities. It is sufficient to start by looking at functional departments, but within each department, distinct activities and the amount of labor used to perform them should be quantified.
   EXAMPLE: The M600 Business Unit, responsible for production of the 600 line of cameras, performs many activities. One of them is "Implementing Engineering Change Notices (ECNs)." On average, this activity requires half a person.
2. Understand the single key variable driving each activity. If one variable cannot be found to adequately represent that activity, further classification may be necessary.
   EXAMPLE: For "Implementing ECNs," Number of ECNs is the driver.
3. Group all activities that share a common driver, and total the amount of headcount associated with that driver.
   EXAMPLE: Number of ECNs drives ECN implementation in the M600 Business Unit, the M7000 Business Unit, the Automation group, the Continuous Engineering group, and the Electrical Engineering (test equipment) group. In total, 5 full-time-equivalent heads are "driven" by Number of ECNs.
4. Quantify the actual amount of the driver for the time period you are analyzing. Divide that into the associated headcount.
   EXAMPLE: In 1998, 145 ECNs were implemented in the factory. Therefore, an ECN requires an average of 5/145 = 0.0345 heads, or about 69 hours, of labor to implement in the factory.
5. Now that you have the actual amount of labor per activity, you can model it for other scenarios. Establish the driver quantity for your what-if scenario, then multiply it by the driver rate.
   EXAMPLE: For the NGP at steady state, 56 ECNs per year are expected (see "Explanation of Key Variables"). Multiplying this by 0.0345 gives us 1.9 full-time-equivalent heads.

Expenses

The ABC process described above can be applied to expenses as well. I simplified this portion of the analysis by using number of indirect headcount as the driver for all expenses. This was a reasonable approach given that the majority of the expenses were headcount-related, such as travel and entertainment; and that the total amount of expenses was less than one third of the total overhead. For factories where expenses the amount of expenses not driven by headcount is proportionally large, a more in-depth ABC analysis is required.

Overhead Spreadsheet Model

The overhead model is represented in a multiple-sheet Microsoft Excel file. The following exhibits are simplified representations of the model.

The first sheet, represented in Table 9, shows the grouping of activities within each VOL department, the full-time equivalent headcount, and the primary driver of each activity. This information is obtained directly from interviews with the managers of each department.

TABLE 9: Activity/Driver Data From Interviews

Department	Activities	Heads	Driver
M600 BU	Sort/move material to cells	6.0	# cells
	Implement ECNs	0.5	# ECNs
	Kaizens & implementation	3.0	# kaizens
	Run/track pilot material	0.5	# new mold tools
	Implement fast track products	3.0	# new parts
	Maintain equipment	1.5	# of fixtures/tools

	Change over cells in response to sched.	1.0	# of schedule changes
	Generate schedule options	1.0	# of schedule options
	Train operators	2.0	# operators
	Count/track WIP	2.0	# parts
	Manage HR issues/success mgmt	2.0	administration
	Create & track budget	1.0	administration
	Implement cost reduction (non-kaizen)	1.5	continuous improvement
	Support India/China/subs w/ advice, parts	0.5	continuous improvement
	Implement yield & cycle time reduction	0.5	continuous improvement
	Implement SAP	1.0	project
	Diagnose quality problems	2.0	yield
	Manage discrepant material	0.5	yield
M7000BU	Sort/move material to cells	1.0	# cells
	Implement ECNs	0.5	# ECNs
	Perform fixtures/ass'y equip maint/upgr	1.5	# of fixtures/tools
	Perform tester maintenance/upgrades	3.0	# of testers
	Train operators	1.0	# operators
	Count/track WIP	1.0	# parts
	Manage product variation	0.5	# PIDs
	Budgeting/HR issues	1.0	administration
	Cost reduction/six sigma	0.5	continuous improvement
	Resolve quality issues	3.0	yield
Automation	Implement ECNs	1.0	# ECNs
	Cost reduction/quality improvement	3.0	continuous improvement
	Install new capacity	4.0	project
Ind. Eng.	Kaizens, cost reduction & implementation	1.5	# kaizens
	Manage schedule changes	0.5	# of schedule changes
	Manage product variation	0.5	# PIDs
	Automation capacity increase	0.5	project
Cont. Eng.	Implement ECNs	2.0	# ECNs
	Fast track development	1.0	# new parts
	Quality improvement	1.0	continuous improvement
	Cost reduction	0.5	continuous improvement
	Support India/China/subs w/ advice, parts	0.5	continuous improvement
Tech. Serv.	Administration	3.0	administration
Elect. Eng.	Implement ECNs	1.0	# ECNs
	Cost reduction	2.0	continuous improvement
	Quality Improvement	2.0	continuous improvement
	EIC instrumentation development	1.0	project
Elect. Mfg	Electronics supplier management	1.5	# electronics vendors
	Support PSL	0.5	continuous improvement
	EIC vendor development	1.0	project
CEL	Perform regular camera testing	6.0	# 600 tests
	Test for failures/ECN qualification	3.0	# 7000 tests
	Supervisor	1.0	administration
	Direct/control lab activities	1.0	administration
	Administration	1.0	administration
	Customer quality data collection/analysis	1.0	continuous improvement
Mat'l Compl.	Tooling maintenance & qualification	1.0	# mold tools
	Tooling gauging & calibration	1.0	# of fixtures/tools
	Resolve material defects - molded parts	2.0	# parts
	Resolve material defects - other	1.0	# parts
	Incoming inspection	1.0	# parts
	Group management	1.0	administration
	Supplier quality plans, other long-term proj	1.5	continuous improvement

	EIC tooling	1.5	project
	EIC DFM, CAD, Quality plans	1.0	project
Personnel	Human resource administration	3.0	site-related
IM	Information systems maintenance	2.0	site-related
Admin	Camera Hardware Manufacturing mgmt	3.0	administration
F&DS	Facilities maintenance	4.0	site-related
Electrical	Facilities maintenance	1.0	site-related
Mat'l Mgmt	Department management	1.0	administration
Prod Planning	Develop and track MPS	1.0	administration
Mat'l Proc.	Manage incoming parts schedules	8.0	# shipments
	Purchasing: manage vendor contracts, PPV	4.0	# vendors
Finance	Create, track, report finances	6.0	site-related
Warehouse	Receive, unpack, store, and issue material	23.0	# shipments
	Handle material queries & inspections	1.0	# shipments
	Team leader	1.0	administration
	SAP installation	1.0	project

By re-sorting the spreadsheet in order of driver (represented in Table 10), the driver-associated headcount is now grouped and can be manually totaled.

TABLE 10: Activity Data Sorted By Driver

Department	**Activities**	**Heads**	**Driver**
CEL	Perform regular camera testing	6.0	# 600 tests
CEL	Test for failures/ECN qualification	3.0	# 7000 tests
M600 BU	Sort/move material to cells	6.0	# cells
M7000BU	Sort/move material to cells	1.0	# cells
M600 BU	Implement ECNs	0.5	# ECNs
M7000BU	Implement ECNs	0.5	# ECNs
Automation	Implement ECNs	1.0	# ECNs
Cont. Eng.	Implement ECNs	2.0	# ECNs
Elect. Eng.	Implement ECNs	1.0	# ECNs
Elect. Mfg	Electronics supplier management	1.5	# electronics vendors
M600 BU	Kaizens & implementation	3.0	# kaizens
Ind. Eng.	Kaizens, cost reduction & implementation	1.5	# kaizens
Mat'l Compl.	Tooling maintenance & qualification	1.0	# mold tools
M600 BU	Run/track pilot material	0.5	# new mold tools
M600 BU	Implement fast track products	3.0	# new parts
Cont. Eng.	Fast track development	1.0	# new parts
M600 BU	Maintain equipment	1.5	# of fixtures/tools
M7000BU	Perform fixtures/ass'y equip maint/upgr	1.5	# of fixtures/tools
Mat'l Compl.	Tooling gauging & calibration	1.0	# of fixtures/tools
M600 BU	Change over cells in response to sched.	1.0	# of schedule changes
Ind. Eng.	Manage schedule changes	0.5	# of schedule changes
M600 BU	Generate schedule options	1.0	# of schedule options
M7000BU	Perform tester maintenance/upgrades	3.0	# of testers
M600 BU	Train operators	2.0	# operators
M7000BU	Train operators	1.0	# operators
M600 BU	Count/track WIP	2.0	# parts
M7000BU	Count/track WIP	1.0	# parts
Mat'l Compl.	Resolve material defects - molded parts	2.0	# parts
Mat'l Compl.	Resolve material defects - other	1.0	# parts
Mat'l Compl.	Incoming inspection	1.0	# parts
M7000BU	Manage product variation	0.5	# PIDs
Ind. Eng.	Manage product variation	0.5	# PIDs

Mat'l Proc.	Manage incoming parts schedules	8.0	# shipments
Warehouse	Receive, unpack, store, and issue material	23.0	# shipments
Warehouse	Handle material queries & inspections	1.0	# shipments
Mat'l Proc.	Purchasing: manage vendor contracts, PPV	4.0	# vendors
M600 BU	Manage HR issues/success mgmt	2.0	administration
M600 BU	Create & track budget	1.0	administration
M7000BU	Budgeting/HR issues	1.0	administration
Tech. Serv.	Administration	3.0	administration
CEL	Supervisor	1.0	administration
CEL	Direct/control lab activities	1.0	administration
CEL	Administration	1.0	administration
Mat'l Compl.	Group management	1.0	administration
Admin	Camera Hardware Manufacturing mgmt	3.0	administration
Mat'l Mgmt	Department management	1.0	administration
Prod Planning	Develop and track MPS	1.0	administration
Warehouse	Team leader	1.0	administration
M600 BU	Implement cost reduction (non-kaizen)	1.5	continuous improvement
M600 BU	Support India/China/subs w/ advice, parts	0.5	continuous improvement
M600 BU	Implement yield & cycle time reduction	0.5	continuous improvement
M7000BU	Cost reduction/six sigma	0.5	continuous improvement
Automation	Cost reduction/quality improvement	3.0	continuous improvement
Cont. Eng.	Quality improvement	1.0	continuous improvement
Cont. Eng.	Cost reduction	0.5	continuous improvement
Cont. Eng.	Support India/China/subs w/ advice, parts	0.5	continuous improvement
Elect. Eng.	Cost reduction	2.0	continuous improvement
Elect. Eng.	Quality Improvement	2.0	continuous improvement
Elect. Mfg	Support PSL	0.5	continuous improvement
CEL	Customer quality data collection/analysis	1.0	continuous improvement
Mat'l Compl.	Supplier quality plans, other long-term proj	1.5	continuous improvement
M600 BU	Implement SAP	1.0	project
Automation	Install new capacity	4.0	project
Ind. Eng.	Automation capacity increase	0.5	project
Elect. Eng.	EIC instrumentation development	1.0	project
Elect. Mfg	EIC vendor development	1.0	project
Mat'l Compl.	EIC tooling	1.5	project
Mat'l Compl.	EIC DFM, CAD, Quality plans	1.0	project
Warehouse	SAP installation	1.0	project
Personnel	Human resource administration	3.0	site-related
IM	Information systems maintenance	2.0	site-related
F&DS	Facilities maintenance	4.0	site-related
Electrical	Facilities maintenance	1.0	site-related
Finance	Create, track, report finances	6.0	site-related
M600 BU	Diagnose quality problems	2.0	yield
M600 BU	Manage discrepant material	0.5	yield
M7000BU	Resolve quality issues	3.0	yield

The second sheet, represented in Table 11, contains the summed data from Table 10 and transforms it into a set of linear equations which are then applied to the NGC portfolios to calculate the amount of indirect labor per unit of each driver. This is also where the volume-driven headcount is introduced. The user must input the portfolio-specific driver quantities for current and future production, production volume, fixed headcount, and project-related headcount.

TABLE 11: Indirect Headcount Model

Driver	Current Production			Next Generation Portfolio			
				NGP		NGU	
	Driver Qty	# Heads Affected	# Heads/ Driver	Driver Qty	Heads needed	Driver Qty	Heads Needed
Activity-Driven							
# shipments/wk	62	32	0.52	46	23.7	66	34.1
# unique parts	950	7	0.01	365	2.7	1141	8.4
# CEL tests	55	9	0.16	77	12.6	110	18.0
# mfg cells	22	7	0.32	26	8.3	27	8.6
# fails/week (yield)	3950	5	0.00	3531	4.5	7062	8.9
# ECNs	145	5	0.03	56	1.9	174	6.0
# kaizens	8	5	0.63	8	5.0	8	5.0
# vendors	66	4	0.06	89	5.4	89	5.4
# new unique parts/yr	60	4	0.07	30	2.0	30	2.0
# fixtures & tools	270	4	0.01	606	9.0	712	10.5
# test tools	50	3	0.06	77	4.6	88	5.3
# operators	360	3	0.01	344	2.9	344	2.9
# schedule changes	12	2	0.17	12	2.0	12	2.0
# mold tools	400	1.5	0.00	566	2.1	810	3.0
# electronics vendors	20	1.5	0.08	3	0.2	18	1.4
# PIDs	101	1	0.01	37	0.4	37	0.4
Total Activity-Driven		94			87.3		121.8
Fixed							
Administration	1	17	17.00	1	17.0	1	17.0
Site-related	1	16	16.00	1	16.0	1	16.0
Total Fixed		33			33.0		33.0
Project/Priority Based							
non-recurring projects	1	11	11.00		0.0		0.0
cont. improvement cost/quality	1	15	15.00	1	7.0	1	15.0
Total Proj/Priority-Based		26			7		15
Volume-Driven							
600 family volume	3E+06	36	0.00	4E+06	48.1	4E+06	48.1
7000 family volume	281000	12	0.00	960000	41.0	960000	41.0
Total Volume-Driven		48			89.1		89.1
TOTAL INDIRECT HC		201			216		259

A similar spreadsheet exists for expenses. As described, I allocated expenses evenly across indirect headcount. In effect, the "activity" is all expenses, and the "driver" is indirect headcount.

Most of the driver quantities in the Overhead Model are direct data or estimates from VOL personnel or come from the Material Model. Some of the driver quantities required more pre-processing, and are described in Appendix F.

Inventory

For the purposes of this discussion there are four types of inventory:

Raw Materials: Material in Polaroid's warehouse
WIP (Work In Process): Material which has been released to the factory floor and is in the process of being transformed into finished products.
FGI (Finished Goods Inventory): Products which are ready to be delivered to customers but have not yet left the factory.

Distribution: Products somewhere between FGI and the paying customer.

In comparing the NGP and NGU, there is no difference (by assumption) between the two in FGI and Distribution, since the differences are at the component, not finished-product, level. For the other two types of inventory, we can look at the VOL site today to understand where the opportunity is. For the existing 600-format camera line, the amount of inventory throughout the first 6 months of 1998 averaged:

Raw Material	29.1 days
WIP	3.4 days

Clearly, in absolute terms WIP is not a significant problem. Polaroid has successfully integrated a Material Requirements Planning system with a shop floor kanban system and single-part-flow cellular assembly. Although there are always opportunities for further reduction, in this environment the difference in WIP carrying costs between the platform portfolio and the unique portfolio would be relatively small in the total cost picture, for two reasons:

1) The *total* amount of inventory carrying cost associated with WIP is relatively small: 3.4 days is 1% of approximately $300 million worth of material (in the NGC portfolios) flowing annually through the facility; assuming a carrying cost of 30% annually, the carrying cost is less than $1 million annually. Even doubling this cycle time to account for the higher complexity of the products results in a starting point of less than $2 million.
2) The difference between the NGP and NGU is likely to be much smaller, because the number of final assembly cells is nearly identical at 26 and 27 respectively and the centralization of common subassemblies is relatively small. (See Capital Costs: Fixtures and Tooling section.) Currently, material is released from the warehouse to a kitting area (becoming WIP) where carts dedicated to each final assembly cell are loaded with a shift's worth of production. Because of this distribution, the amount of WIP becomes a function of number of final assembly cells, not the number of unique parts.

Because of the minimal effect on total cost, it was deemed unnecessary to perform detailed shop-floor WIP modeling. Given the factors described above, I simply estimated WIP for the NGC portfolios as:

NGP: 5 days
NGU: 6 days

The expansion from 3.4 days to 6 days reflects the higher volume and complexity of these products. As described, the difference between the NGP and NGU portfolios is unlikely to be significant, certainly no more than 1 day.

Turning our attention to Raw Material, we have a wide array of inventory modeling tools to choose from. At the most general level, inventory can be expressed as a sum of two components.

Inventory = Cycle Stock + Safety Stock

Cycle stock is the amount of raw material inventory needed to supply production in the time span between regular deliveries of more raw material. Safety stock is the amount of inventory needed to cover uncertainty of all types, such as upward fluctuations in demand or yield loss, which consumes more raw material; late deliveries; and deliveries of nonconforming material. Given historical data on these variances and a desired *service level*, or percentage of time the operation will deliver to the customer on time, one can determine how much safety stock one needs.

Since the cycle stock is a function of end-product demand and delivery frequency, it is not affected by the question of platform vs. unique architecture. The platform approach does allow you to reduce your safety stock, however. It does this by pooling the *variance* in end-product demand. Conceptually, if demand for one of our six products fluctuates *upwards* in a time period, it is highly probable that demand for at least one of the other five products will fluctuate *downwards*. For components that are shared across products, the effect is that the fluctuations cancel each other out. Instead of maintaining six separate safety stocks for six different components for six products, you might have just one safety stock for one component for six products. Assuming that the demand for each product is normally distributed and independent of the other products, the size of that safety stock is reduced by the square root of the number of products:

$$SS_{common} = \frac{SS_{unique}}{\sqrt{N}}$$

where:

SS_{common} = Safety stock of a component shared across N products
SS_{unique} = Sum of the safety stocks for that component if it was unique to each of the N products

With the end-product demand variances and the other variances known, it is possible, through the use of statistical methods, to quantify the difference in required safety stock, and therefore total inventory, between the NGP and NGU. For both NGC portfolios, these variances are unknown; furthermore, past data was inadequate to construct estimates. However, we can reasonably estimate the difference in required raw material inventory through some simple observations:

1. For the 636 line in production today, raw material inventory averages 29 days, and service level targets are being met. Therefore 29 days is a reasonable starting point.
2. Target safety stocks are currently defined by policies which reflect certain operating conditions. (They may or may not be statistically based.) For example, safety stock for camera bodies is set to half a day, because the VOL factory receives just-in-time shipments from local suppliers. Safety stock for electronics components is set to two weeks because most of the electronics suppliers are located in the Far East. For problem suppliers and older mold tools, safety stock is set even higher. Because the NGC portfolios have a high electronics content (>60% in dollar terms), it appears reasonable to assume that safety stock for the NGU would be on average two weeks.
3. If the six cameras had 100% component sharing – in other words, if they were virtually identical but still subject to different end-demand – the new safety stock would be 14/sqrt(6), or 5.7 days. If the cameras had 0% sharing, then we would have the original 14 days.
4. The number of unique parts seen in the VOL factory for the NGU is 1141, and for the NGP is 365. Thus the level of sharing is approximately 1 - 365/1141 = 68%.
5. Bounded by 5.7 days and 14 days, 68% sharing would result 5.7 + (14 - 5.7)*(1 - 0.68) = 8.4 days.
6. We said of the original 29 days of raw material, two weeks or 14 days was safety stock. This leaves a cycle stock of 15 days. Adding the estimate of 8.4 days of safety stock for the NGP gives us 23.4 days.

To summarize, the predicted inventory for both portfolios is:
NGP: 23.4 days raw material + 5 days WIP = 28.4 days
NGU: 29 days raw material + 6 days WIP = 35 days

V. TOTAL COST

The costs from each sub-model are calculated as shown in the appendices and are summarized and totaled here. The costs can be classified into two categories: initial costs, which are a one-time expenditure, and recurring annual costs. For the annual costs, the net present value of the costs over ten years are calculated, using a cost of capital of 20%. (Note: On the books, capital equipment is an asset which is depreciated over ten years, but from a cash flow point of view, it is an initial expense, so I've presented it that way.) The results are shown in the table below. The platform approach to the NGC portfolio costs 13.5% less than the unique approach, for a total savings of $223 million over 10 years, net present value. A brief discussion of each cost component follows.

TABLE 12: Total Cost Summary

	NGU	NGP	Savings	% Savings	% of Total Savings
Initial Costs					
D+d	70.6	30.1	40.5	57.4%	18.2%
Capital	45.1	39.8	5.3	11.8%	2.4%
Inception	41.3	20.3	21.0	50.8%	9.4%
Annual Costs, 10 yrs, NPV					
Mfg OH	82.7	70.3	12.5	15.0%	5.6%
Inv.Carrying	37.6	27.4	10.2	27.1%	4.6%
Labor	61.4	60.9	0.5	0.8%	0.2%
Materials	1308.7	1175.8	132.9	10.2%	59.6%
TOTAL	**1647.4**	**1424.6**	**222.8**	**13.5%**	**100%**

Development. The percentage cost savings is the greatest in this category. This is because design re-use is nearly free. The savings is offset somewhat by the initial engineering effort required to plan a set of products, but the effect is minimal in this case. It should be noted that design re-use becomes more expensive if the original design is handed off to someone else, since the originator must spend more time on documentation and because the new person must spend time becoming familiar with the design. This has important implications for maximizing the benefit of platform design: ideally, all products within the platform are designed by the same team.

Capital. The capital cost figure in the table is the sum of mold tooling costs and factory equipment costs. The vast majority of the capital savings comes from the use of mold tooling with a greater number of cavities per mold, justified by the "fewer different parts, higher volume per part" result of component sharing. The savings in assembly and test factory equipment is minimal, for three reasons. First, compared to mold tooling, factory equipment expenditures are small. Second, the number of final assembly cells is virtually the same, since this is the point at which products are differentiated; most of the products must be assembled on different cells. Even in the case where different products could be assembled in the same cell (the EIC and the PIC), there may not be a need to if multiple cells are required for each product in order to meet demand. Finally, savings from automation is minimal, since the only additional automated subassemblies in the NGP are the EIC and PIC shutter assemblies.

Inception. Savings in inception costs are more dramatic, since inception is modeled as a linear function of unique part count.

Manufacturing Overhead. While the reduction in manufacturing overhead from using the platform approach is a respectable 15%, it is not the dramatic 50%+ seen in development and inception. This is for two reasons: First, there is a large component of the overhead that is essentially fixed, given some nonzero level of production. Second, the variable portion of overhead is a function of many different variables, only one of which is total part count.

Inventory Carrying Cost. Almost all of the inventory carrying savings comes from reductions in raw materials. There is no savings in finished goods inventories, since once a product is assembled it is irrelevant whether it shares part designs with other products. Savings in WIP is minimal, since Polaroid's shop floor assembly operation is already lean and since materials must be allocated to each final assembly cell, the total number of which is virtually the same in both scenarios. For raw material, sharing components across different products allows you to pool the variation in demand. Thus, safety stock quantities can be reduced while maintaining the same level of on-time delivery of materials to the assembly floor.

Labor. Reduction in labor is minimal; in this model it comes only from automating the EIC and PIC shutter assembly.

Materials. In absolute terms, the greatest savings comes from the annual recurring costs, primarily in materials: although the cost reduction in materials is only 10.2%, the contribution to total savings is nearly 60%. This is because materials costs constitute the vast majority of total costs. The 10% savings comes from achieving greater volume discounts from the "fewer different parts, higher volume per part" result. Whereas for development, where design reuse is virtually free, for materials purchasing you still have to pay for the second part; you just get it at a higher volume discount.

Sensitivity Analysis

The analysis up to this point has used a fixed set of values for each of the input variables. These are of course subject to error and to change over time. It is thus useful to understand which of those input variables have the greatest effect on total cost, and to what degree. Examination of the model reveals that two sets of variables have a significant impact on total cost:

1) The number of unique parts (part numbers)
2) The materials economies of scale, for example the 25% reduction in price for electronics parts for every 10X increase in volume.

Number of unique parts

The number of unique parts is the variable at the heart of this platform analysis, since it reflects the amount of component sharing across products in a portfolio. Therefore, it is desirable to determine the impact to total cost from decreasing the number of unique parts (increasing the number of shared parts). It is not efficient to construct an equation to directly model total cost as a function of unique parts, since the result depends on exactly which parts are shared and which are not. However, given two realistic boundary conditions, we can create a line from which we can determine the average amount of savings from each additional shared part. The two portfolios we have investigated represent those boundary conditions, since the NGU has no shared parts and the NGP shares as many parts as possible without significant cost compromise and while still meeting the different specifications for each product. The form of the equation is simply:

Total Cost = (Cost per Unique Part) x (Number of Unique Parts) + Constant

With our two portfolios, we have two equations

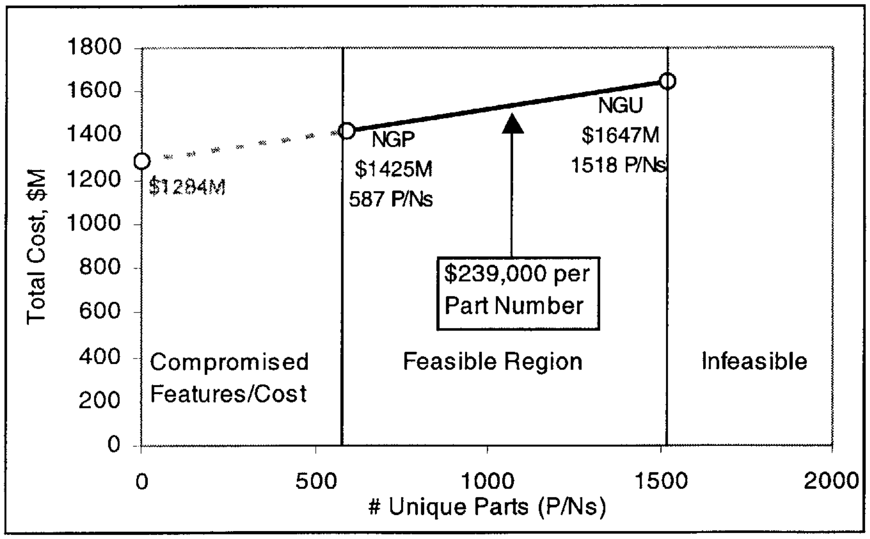
\$1424.6M	= Cost per Unique Part x 587 Unique Parts + Constant	(NGP)
\$1647.4M	= Cost per Unique Part x 1518 Unique Parts + Constant	(NGU)

Solving, we find that the Cost per Unique Part is \$239,000, and the constant term is \$1284M. Thus the equation for total cost as a function of number of unique parts is simply:

Total Cost = \$239,000 x Number of Unique Parts + \$1,284,000,000

Stated intuitively, this means that designing and producing the Next Generation Camera portfolio in the forecasted quantities over 10 years will cost \$1284M plus \$239K for every unique part number. The important term here is the \$239K per part, because the equation is not to be trusted below the boundary of 587 unique parts. Below that number, we start compromising the features and component choices for the products. The best way to use this equation is to say, "Within the boundaries of the unique portfolio and the platform portfolio as defined, every unique part number we can eliminate through sharing will save us approximately \$239,000. Of course, this is based on the assumption of a linear relationship." Figure 3 below illustrates this function.

FIGURE 3: Total Cost As A Function Of Part Count



Materials economies of scale

Materials economies of scale affect only materials costs and mold tooling cost. We are interested in what happens if the economies of scale are less than predicted – in other words, what is the "realistic worst case?" The following table compares the inputs to the original model with those of the worst case:

TABLE 13: Scale Economy Rules for Sensitivity Analysis

COST CATEGORY	SCALE ECONOMY- ORIGINAL	SCALE ECONOMY – WORST
Mechanical Parts	5% reduction for 2X volume	2% reduction for 2X volume
Optical Parts	5% reduction for 2X volume	2% reduction for 2X volume
Electronics Parts	25% reduction for 10X volume	10% reduction for 10X volume
Molded Parts	40% reduction for cavity doubling	30% reduction for cavity doubling
Mold Tooling Capital	40% increase for cavity doubling	60% increase for cavity doubling

The rules for parts prices were simply entered into the Material Model and automatically calculated. Note that the new rules affect the unique portfolio also, so the total cost of the unique portfolio must be calculated both ways for appropriate comparison. The mold tooling capital required a little algebra, identical to that shown in the Capital Costs section. The only difference is that a capital increase factor of 1.6 is used instead of 1.4. The results are summarized below.

TABLE 14: Total Cost Sensitivity To Scale Economy Rules

Category	ACTUAL (ORIGINAL CASE)			LOWER ECONOMIES (WORST CASE)		
	Unique	Platform		Unique	Platform	
	$M	$M	Δ vs. unique	$M	$M	Δ vs. unique
Materials	1308.7	1175.8	10.2%	1516.3	1434.0	5.4%
Capital	45.1	39.8	11.8%	52.8	44.8	15.2%
All else	293.6	209.0	28.8%	293.6	209.0	28.8%
TOTAL	1647.4	1424.6	**13.5%**	1862.7	1687.8	**9.4%**
Savings		222.8			174.9	

Interestingly enough, both the percentage and absolute savings in capital equipment is greater under the worst-case scenario. This is because the worst-case impact to mold tooling for the unique portfolio is more significant than the impact to mold tooling for the platform portfolio. Overall, however, the total savings under the worst-case scenario is 9.4%, down from the 13.5% in the original case.

VI. SUMMARY

Using a combination of detailed spreadsheet models and simple calculations, I quantified the cost benefits of the platform design approach for a specific portfolio of six cameras. The savings is predicted to be 13.5%, with a worst-case prediction of 9.4%. The results are strongly a function of the level of component sharing and design re-use. While the results might be significantly different for computers, cars, or even a different set of cameras, one result seems more general: The percentage cost savings is greater in the initial costs of design and development than in recurring manufacturing costs. Intuitively, it can be explained this way: In development, you can re-use part of a design for another product for almost no incremental cost. In manufacturing, you still have to buy, manufacture, and assemble the second part; you just get a discount because of the economies of scale from sharing.

Beyond the computation for this specific portfolio of cameras, I have also provided some tools and methods for performing this analysis for other products. A potential stumbling block is that the approach requires a Bill of Materials for each product in the portfolio. In practice, it may be unrealistic to create these documents in advance of the decision of what products to design and how to design them. However, highly simplified versions of the BOMs are sufficient, as long as they contain the components that represent the majority of the product costs and decisions to be made.

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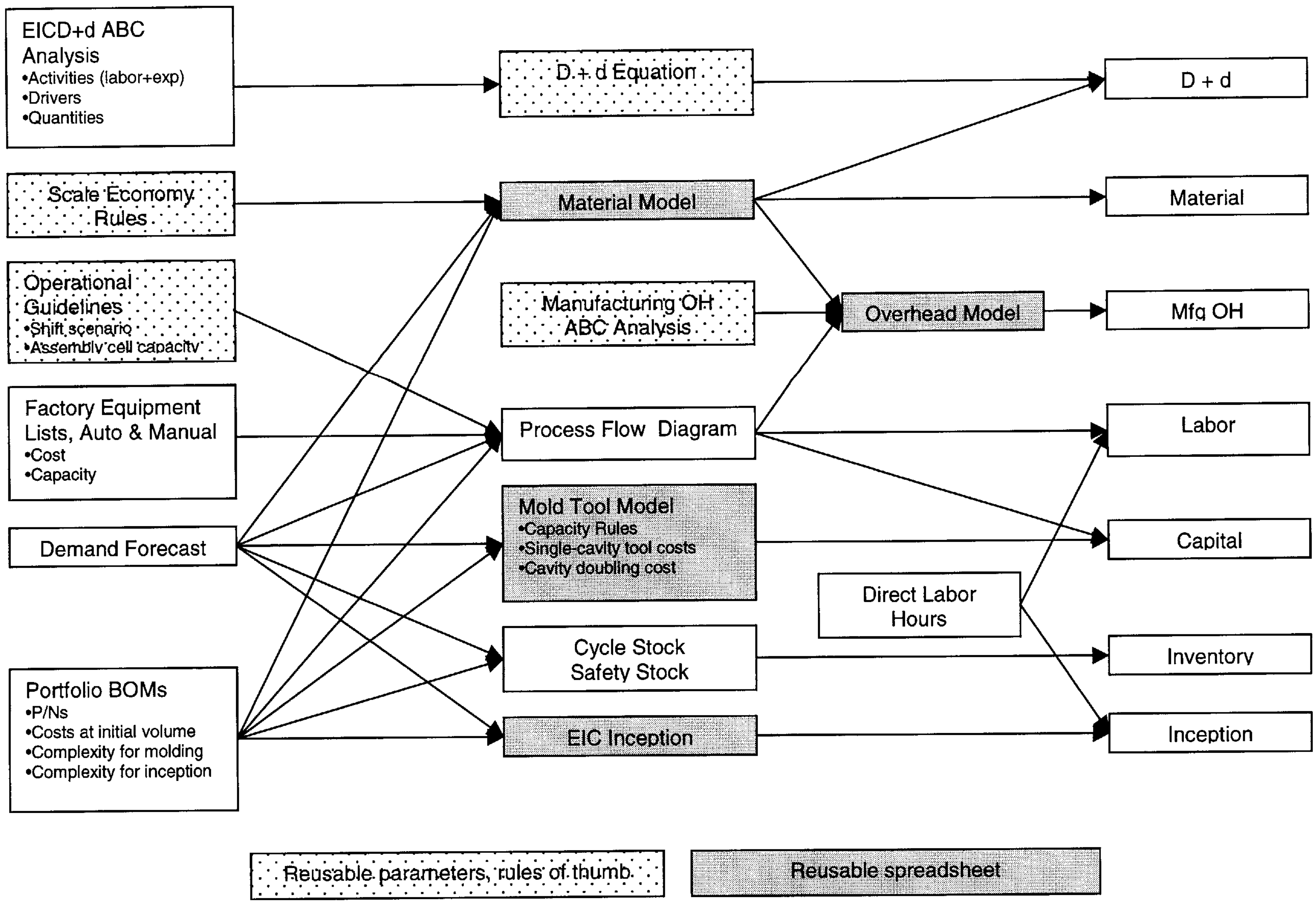
APPENDIX A: ANALYSIS PROCESS



DISCLAIMER

APPENDIX B: MATERIAL COST CALCULATIONS

For this project I had only a BOM for the EIC product, since the other products are not yet designed. The EIC BOM, in grouped format, looks like this:

TABLE B-1: EIC Bill of Materials, Condensed Form

EIC Subsystem	Mechanical		Molded		Electronic		Optical		PCB
	# P/Ns	Cost	# P/Ns	Cost	# P/Ns	Cost	# P/Ns	Cost	
PI Shutter	4	0.54	2	0.32	1	1.96			
PI Focus	4	0.59	6	1.29	1	1.96	4	2.98	
EI Acquisition	14	1.79			1	3.62	6	5.78	
Spread/Drive	14	3.04	8	1.07	1	2.00			
Door	6	1.98	3	1.37					
Mainframe	7	0.24	15	1.61	2	0.24			
Frontplate Ass'y	6	1.21	4	2.93			1	0.44	
Final Assembly	19	4.65	17	5.18			3	2.13	
Packaging	4	1.04			2	1.44			
Interconnect					3	3.73			
Display LCD					1	20.00			
Misc. Electronic					3	32.68			
IR Ranging	3	0.19	2	0.30	18	3.24	1	0.28	0.75
CCD Board					10	23.95			2.35
CCD Support Board					33	19.62			0.92
Mainframe Flex					10	5.26			3.00
Power Conv. Board					60	14.15			2.75
Main Board					94	33.71			3.81
Inverter Board					11	1.61			2.00
Trigger Board					8	3.58			1.51
User Interface + Compact Flash					9	6.15			1.00

From interviews with the engineers on the EIC team, I constructed de facto BOMs for the other products. Instead of being complete lists, however, they are simply lists of what would be different about the EIC to make it an ESC or PIC or the other three. This incremental approach eliminated the need to create entire bills of materials. It also keeps the material model simpler, because parts can be grouped. For example, the PI Focus Subassembly is represented in the NGP material model as:

TABLE B-2: Material Model, PI Focus Subassembly, NGP

						Costs at EIC-only volume of 100K units/year							
EIC	ESC	EIP	PIC	PMF	600	Mechanical		Molded		Electronic		Optical	
						# P/Ns	$ cost	# P/Ns	$ cost	# P/Ns	$ cost	# P/Ns	$ cost
1			1	1	1	3	0.43	2	0.33			2	1.24
1			1	1		1	0.06	2	0.40				
1			1					2	0.56	1	2.96	2	0.84
				1	1					1	1.00	2	1.34

This means, for example, that there are 3 mechanical components, costing a total of $0.43 at volumes of 100K per year, which are common to EIC, PIC, PMF, and HB600. The annual volume of those 4 cameras can be summed, and through a logarithmic calculation described below, the 5% reduction per volume doubling can be applied and the cost of those 3 components can be calculated at that volume.

The NGU material model reflects the lack of commonality of any of the parts:

TABLE B-3: Material Model, PI Focus Subassembly, NGU

						Costs at EIC-only volume of 100K units/year							
EIC	ESC	EIP	PIC	PMF	600	Mechanical		Molded		Electronic		Optical	
						# P/Ns	$ cost	# P/Ns	$ cost	# P/Ns	$ cost	# P/Ns	$ cost
1						4	0.49	6	1.29	1	2.96	4	2.08
			1			4	0.49	6	1.29	1	2.96	4	2.08
				1		4	0.49	4	0.73	1	1.00	4	2.58
					1	3	0.43	2	0.33	1	1.00	4	2.58

What this shows is that, for example, there are 4 mechanical parts costing $0.49 in the EIC; 4 different mechanical parts, also costing $0.49, in the PIC; and so forth. Note that neither the ESC nor the EIP have any PI Focus Subassembly components. This is because they are digital-only cameras and hence do not use this subassembly.

The formula which calculates part price for a given volume is as follows:

$$P = P_0(1-a)^{(\log V - \log V_0)/\log b}$$

where:

P = part price
V = volume
P_0 = price at volume V_0
a = percent price reduction for every b times increase in volume. $0 \le a \le 1$

This formula is valid for all part types except for molded parts. The cost of molded parts is dependent upon the number of cavities per mold tool. See the Capital cost section for a description of that calculation.

APPENDIX C: DEVELOPMENT COST CALCULATIONS

Activity Data. From financial and payroll records through November 1998, I extracted the number of labor hours for each activity in the EIC project. Through interviews, I extrapolated the remaining D+d labor hours by activity required to finish the project. I then analyzed the EIC BOM to quantify each driver for the EIC project. The results are summarized here:

TABLE C-1: EIC Activities and Drivers

ACTIVITY	EIC ACTIVITY QUANTITY	DRIVER	EIC DRIVER QUANTITY
Mechanical Design	42,226 hours	Number of unique mechanical parts	158
Electrical Design	56,473 hours	Number of unique electronic parts	210
Purchasing	1200 hours	Total number of unique parts	368
Final Assembly Cell Design Product Documentation	2612 hours	Number of major products	1
Program Management CAD Object Library Design	6099 hours	Fixed	N/A

Expense allocation. Expenses totaled \$3,418,183, and labor (at a loaded average of \$129 per hour) totaled \$14,010,690. Because expenses are not strongly weighted by either mechanical or electrical design, and because they are relatively small (less than 20% of total), I simply allocated expenses evenly to every labor hour, regardless of the specific labor activity. Thus the fully loaded labor rate becomes \$160.47.

Creating the equation. By dividing the activity quantity by the driver quantity and multiplying by the fully loaded labor rate, we find the cost per unit of each driver. For example, 42,226 hours of mechanical design, divided by 158 mechanical parts, multiplied by \$160.47 per hour, results in \$42,886 per mechanical part. Carrying this out for all drivers yields an equation we can apply to the Next Generation Camera portfolios – with one exception. We must also include the up-front costs for platform planning. One of the tradeoffs of the platform design approach is that it requires additional planning and conceptualization in advance, since an entire architecture must be designed and roughly optimized. In this case, it is estimated that about 4 man-years, or approximately \$1 million, were devoted to this planning and conceptualization before the EIC was formally kicked off. This is added to the total D+d for the NGP. Thus the final equation is:

$$D+d = \$42{,}886M + \$43{,}153E + \$523T + \$419{,}148P + \$1{,}000{,}000NGC + \$978{,}707$$

where:

$D+d$ = Total product and manufacturing development cost
M = Number of unique mechanical parts
E = Number of unique electronic parts
T = Total number of unique parts = M + E
P = Number of major products
NGC = 1 for the Next Generation Platform portfolio, 0 for the Next Generation Unique portfolio

Calculating D+d for the portfolios. The data in the following table is derived from analysis of the BOMs for the NGP and NGU portfolios.

TABLE C-2: Driver Data for NGC Portfolios

	M	E	T	P	NGC
NGP	251	336	587	6	1
NGU	665	853	1518	6	0

Plugging those values into the equation for D+d, we find:

D+d(NGP) = \$30,064,390 and D+d(NGU) = \$70,616,208

APPENDIX D: MOLD TOOLING CAPITAL COST CALCULATIONS

As described in Appendix B, for this analysis condensed Bills of Materials were used. As a result, we have groups of parts rather than individual parts. For each group of parts, the average part complexity was established. Then, for both portfolios, the spreadsheet calculates the total number of tools and the average number of cavities per tool:

NGP: 566 tools, 3.0 cavities per tool
NGU: 810 tools, 2.1 cavities per tool

To translate this into a cost, we need to know the average cost of our mold tools. To further simplify the analysis, I used the overall average tool price as the initial price for the entire group of tools. For the EIC, which uses all single-cavity tools, I found from the original BOM an average cost of $22,107 per tool. (Excluded from this calculation are optical components, which are manufactured in-house with 4-cavity tools, regardless of volume.) I then applied the 1.4X factor to find that a 2-cavity tool costs $30.9K and a 4-cavity tool costs $43.3K. Taking a linear average, the average cost per tool for the NGP portfolio (3.0 cavities per tool) is $37.1K, and for the NGU (2.1 cavities per tool) is $31.5K.

Note that this is an approximation, because we did not calculate the tooling requirements for each specific part. With extensive modification, the spreadsheet could be altered to perform this calculation. However, the intermediate step of calculating the total number of required tools and the average cavities per tool serves two useful purposes: 1) We need the number of tools for use in the Overhead Model; and 2) It is instructive to see these variables directly and understand how tool count decreases while capacity per tool increases.

With our tool count and average cost per tool in hand, we see that the NGP requires

566 x $37.1K = $20,999K

and the NGU requires

910 x $31.5K = $25,515K

APPENDIX E: FACTORY EQUIPMENT CAPITAL COST CALCULATIONS

Guidelines for Process Flow Diagram creation:

- Because of significant differences in final assembly, the EIC, ESC, EIP, and HB600 must have different, dedicated final assembly cells.
- The PIC and PMF can share the EIC final assembly cell due to the folding nature of these cameras. The three products cannot be assembled simultaneously, however; a changeover of fixtures requiring about an hour is required.
- If a subsystem is common only to products which share a final assembly cell, then there is no need to create a separate subsystem assembly cell; the assembly can be integrated into the final assembly cell.
- Subassemblies are automated when volume is at least 1,000,000 units per year. Previous Polaroid NPV analyses have validated this breakpoint.
- With the exception of the HB600, the capacity of every final assembly cell is 400 units per shift. This corresponds to a takt time of 45 seconds per camera and a rate efficiency of 62.5%, meaning that the other 37.5% of time accounts for breaks, maintenance, slowdowns, and other causes of line stoppage. This approximation is robust because it is bounded by a relatively complex product, the EIC, which is planned for 400 units per shift; and by the current relatively simple product, the 636CL, which is assembled in cells with a capacity of 450 units per shift, only 12% higher. Thus it is reasonable to assume 400 units per shift per cell for all products, with the exception of the HB600, for which we will use 450 units per shift because of its similarity to the 636CL.
- We will assume 2 shifts per day, 5 days per week for manual assembly and 3 shifts per day, 7 days per week for automated assembly. For manual assembly, the VOL factory currently runs 1 shift 5 days per week with a variable second shift, which has been used at about 50% year-to-date. For automated assembly, the VOL factory currently runs 3 shifts per day, 5 days per week. Because our scenario has higher volumes, we will use more of the 2nd shift and require full-time use of the automated assembly lines.

Manual Subassembly Production

The only manual subassembly which can be shared in the NGP is the LCD Assembly. This is the LCD screen, gasket, and bracket which together as a completed subassembly attaches to the camera body in final assembly. The process time for this step is 35 seconds, meaning that the equipment is utilized only 78% of the time during production. The true capacity of the fixturing is 513 units per shift, not 400. Total volume is 660,000 units per year, or 1320 per shift. By consolidating this operation into one cell area, we need 3 copies of the fixturing, not the 5 required by providing to one each of the EIC, ESC, and 3 EIP final assembly cells. At $3500 per copy:

NGP: $10,500
NGU: $17,500

Automated Subassembly Production

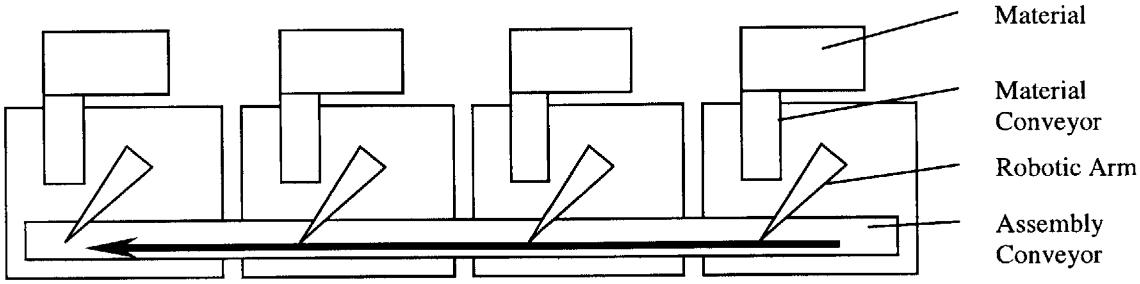
The cost of automation includes the following:

- The capital cost of the automated equipment
- The engineering labor required to customize it to a particular design
- The labor required to operate and maintain the equipment

The savings from automation come from elimination of assembly labor and manual assembly equipment

Description. Polaroid currently uses flexible automation for several subassemblies, and has deep expertise in customizing the system for its specific products. As such I assume that for the Next Generation portfolio, Polaroid would continue to leverage its assets and expertise in this area. The system consists of robots sourced from Sony Corporation. Each robotic arm has up to six turrets on it, allowing it to pick up to six different components. The end effector on each turret is custom-designed to the specific component, and the robot movement sequences must be custom-programmed. Past each arm runs a conveyor with the product assembly on it. The pick and place time for each component, the total number of components, and the required capacity determine how many robots are linked sequentially and how many of the six turrets are used. Material is fed from the side of the robot opposite the assembly, with a combination of bowl feeders, shakers, and trays. The representation below summarizes these concepts:

FIGURE E-1: Polaroid Flexible Automation System



Capacity. The capacity of each robot depends on the size, shape and complexity of each piece part. A comparison between two 636 subassemblies shows that these differences are minimal: the 636 shutter unit requires using, on average, one robot for every 1.71 parts, whereas the drive unit requires a very similar 1.77 parts per robot, for the same capacity of 2100 units per shift. It should be noted that these subassemblies are similar in the size and complexity of their parts; dramatically different assemblies, such as final assembly, would require more robots per part. However, we will use the average 1.74 parts per robot, for a capacity of 3654 parts per robot per shift.

Cost. Each robot costs about $80,000 and requires about 0.5 persons to operate and maintain it. At an annual labor cost of $50,000 per year per person in the VOL, over 10 years assuming a 20% discount rate and annual wage increases of 5%, the labor is $111,600. Thus the cost per robot is $191,600K.
It is conservatively estimated that for each distinct subassembly, 3 man-years of engineering effort are required to design and implement custom end-effectors and programming routines. This is approximately equivalent to $300K in Scotland.

Number of robots needed. The tables below show the distinct subassemblies in each portfolio and the associated robot requirements, based on the sales volumes and shift scenarios previously described. The quantity of robots is calculated by multiplying the number of parts by the per-shift volume, then dividing by the robot capacity of 3654 parts per shift and rounding up to the next integer

TABLE E-1: Robot Capacity Requirements for NGU

NGU: 6 distinct automated assemblies			
Subassembly	# Parts	Vol/Shift	Robots
PMF Shutter	7	952	2
600 Shutter	7	3046	6
PMF Door/Drive	31	952	9
600 Door/Drive	31	3046	26
PMF Focus	17	952	5
600 Focus	12	3046	10
TOTAL			58

TABLE E-2: Robot Capacity Requirements for NGP

NGP: 4 distinct automated assemblies			
Subassembly	# Parts	Vol/Shift	Robots
EIC/PIC/PMF/600 Shutter	7	4379	9
PMF/600 Door/Drive	31	3998	34
PMF Focus	17	952	5
600 Focus	12	3046	10
TOTAL			58

Note that the number of robots is the same in both scenarios. However, in the platform scenario we added the EIC and PIC shutter to the robot lines. Thus we must look at the savings from the labor and manual equipment we eliminated. The labor savings is captured in the Labor chapter. The equipment cost is $23,200 for 2 lines. Additionally, the ultrasonic staking fixture could be made simpler since it wouldn't have to stake both the IR Subassembly and the PI Shutter, for a savings of about $10,000.

Thus the total costs associated with automation are:

NGU: 6x$300K + 58x$191,600 + $33,200 = $12,616,000

NGP: 4x$300K + 58x$191,600 = $12,312,800

Final Assembly Cells

We must estimate the total amount and cost of factory equipment necessary for all products in both portfolios. We have a detailed list of the equipment, grouped by subassembly, for the EIC. By using the Product-Subassembly Matrices (Exhibit X) and knowledge of the differences within subassemblies, I estimated the cost and quantity of equipment for the other products in the Next Generation Platform portfolio. The total cost of that equipment is $6,463,000. Then, as the Process Flow Diagram indicates, the only difference between the NGP and the NGU is the cost of one PIC cell, which is $514,000. Thus the total final assembly cell costs are:

NGU: $6977K

NGP: $6463K

The total factory equipment capital costs are then

NGU: $11K + $12,616K + $6977K = $19,604K

NGP: $18K + $12,313K + $6463K = $18,794K

APPENDIX F: MANUFACTURING OVERHEAD COST CALCULATIONS

Most of the driver quantities in the Overhead Model are direct data or estimates from VOL personnel or come from the Material Model. Some of the driver quantities required more pre-processing, and are described below.

Shipments per week. The largest single pool of indirect labor in the VOL is the material handling group. Fully 32 people are responsible for taking delivery of shipments, storing material in the warehouse, moving material to the production floor, and processing all the associated transactions with MANMAN, the MRP system. The manager of this group believes that the primary driver of this labor is the rate of shipments received. Reducing the number of unique parts, however, does not have a linear effect on the rate of shipments. In fact, in addition to number of unique parts, shipment rate is a rather complicated function of delivery frequency, order size, and demand variability, all of which are different for different parts. In order to simplify the estimation, the materials manager estimated that a 50% reduction in the number of unique parts would result in a 20% decrease in the number of shipments. From that guideline the following function can be derived:

$$S = S_0(1-a)^{(\log X - \log X_0)/\log(1-b)}$$

where:

S = Number of shipments
S_0 = Initial number of shipments
X = Number of unique parts
X_0 = Initial number of unique parts
a = Percentage reduction in number of shipments if number of unique parts is reduced by b (%)
$0 \le a \le 1$
$0 \le b \le 1$

Number of unique parts. Number of unique parts is obtained by starting with the total from the Material Model. Then, the parts which come attached to circuit boards are subtracted, since from an activity perspective in the factory, a fully populated circuit board is only one part.

Further modification is required. The Material Model assumes exactly one variant for each of the six cameras. While this makes the analysis simple, it is not realistic. See the table below, which shows the number of end-product variants and number of unique parts in the VOL today.

TABLE F-1: Quantity of Part Numbers and Variants For Current Products

CAMERA LINE	# PNs IN BASE MODEL	TOTAL # PNs	TOTAL # VARIANTS
600	105	700	76
7000	~150	250	25

Polaroid has embarked on a strategy of reducing the total number of variants. While it does not know the exact savings from this strategy, the company is aware that variants add many hidden costs, and that a significant number of the variants are probably not necessary. For example, there are several different colors of buttons to meet the perceived unique color needs of different regions. Differences such as these which are difficult to justify are being eliminated. To that end, it is reasonable to assume that the number of variants in the NGC portfolios will be significantly reduced. To keep the analysis simple while largely accounting for variants, I assume that the total number of HB 600 and PMF unique parts will be 3 times the number in the base models (vs. the current 7X for the 600 line); and that the remainder of the cameras will have no variants beyond the base model.

Since the PMF and the 600 unique cameras have unique part counts of 119 and 106 respectively, this results in a total unique part count of (696 – 119 – 106) + 3x(119+106) = 1141 for the NGU. For the NGP the number of incremental 600 and PMF parts is 44; therefore the total is 277 + 2x(44) = 365.

Number of Engineering Change Notices (ECNs). In the most recent year there were 145 ECNs at the VOL. For 950 parts, this works out to 1 ECN per year for every 6.6 parts. Applying this ratio to the platform portfolio gets us 56 ECNs per year; to the unique, 174 ECNs per year. This approach is valid if the ECNs are evenly distributed across type of part. For example, if all ECNs were for the types of parts which change whether the portfolio is platform-based or unique, such as external shells, then there should be no difference between the platform and unique portfolios. My examination of the list of ECNs revealed no pattern or concentration on types of parts.